Metallic Fuel Development

Steven L. Hayes

Argonne National Laboratory

AFCI Semi-Annual Review Meeting

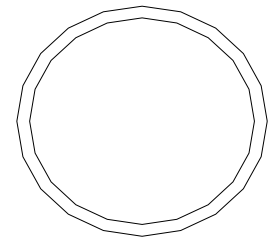
Santa Fe, NM

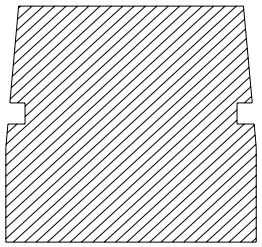
August 27, 2003

Outline of Presentation

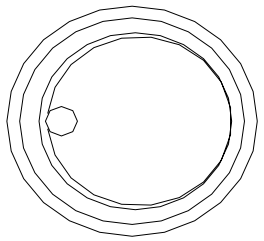
- Fabrication
  - Metallic Fuel Fabrication Process Development
  - Test Fuels and Sample Production
  - Rodlet Fabrication (Metallic and Nitride Fuels)
- Characterization
  - Chemical Analysis & Isotopics on Fuels
  - Microstructural Analysis
  - Thermal Analysis
  - Fuel-Cladding Compatibility
- Irradiation Test Fabrication and Assembly
- Postirradiation Examination

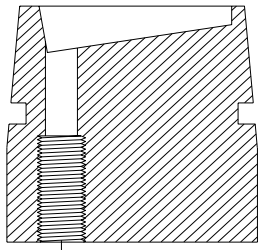
Metallic Fuel Fabricated by Arc-Casting

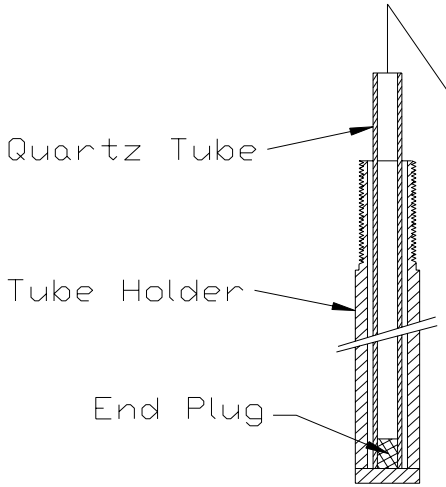




Blank
Hearth

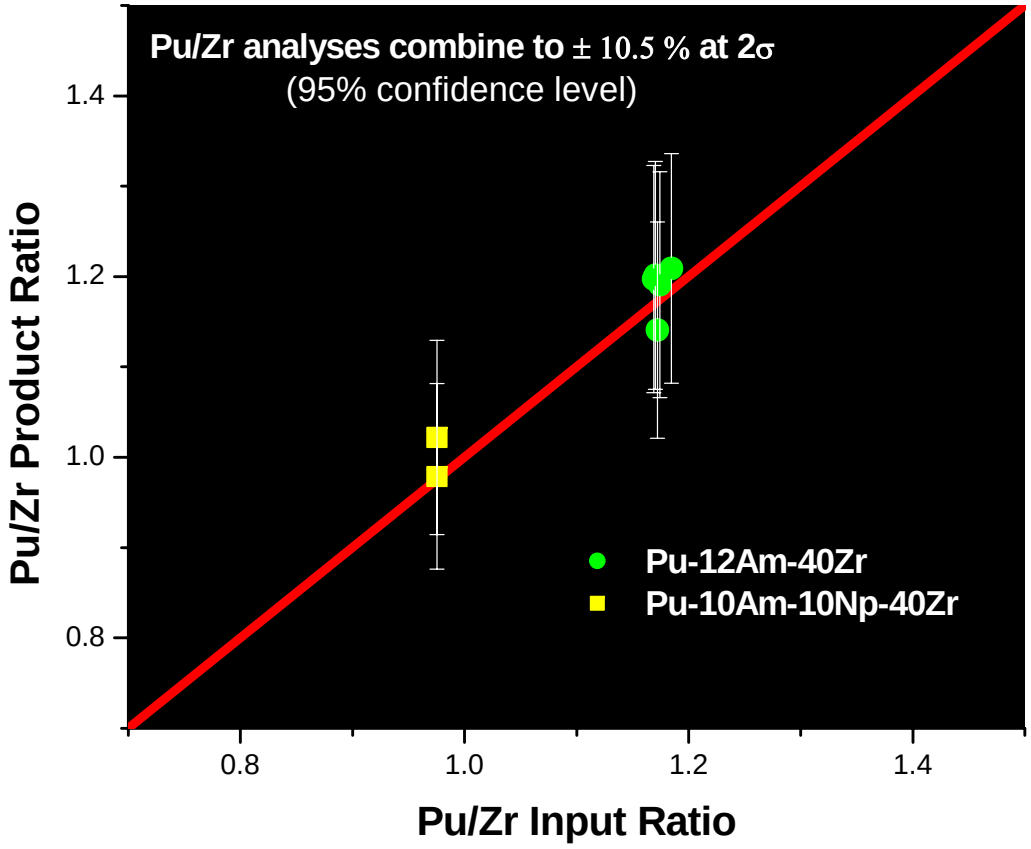




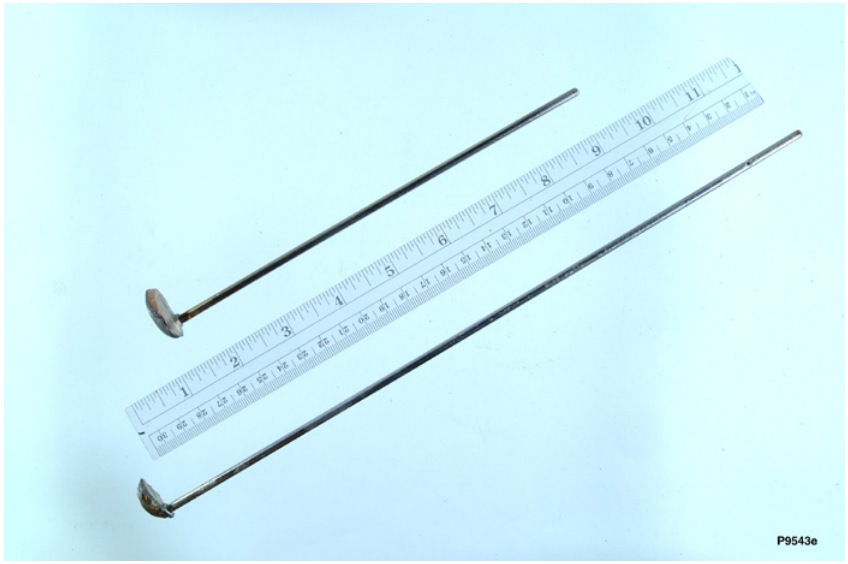


Modified Hearth

No Americium Loss During Arc-Casting

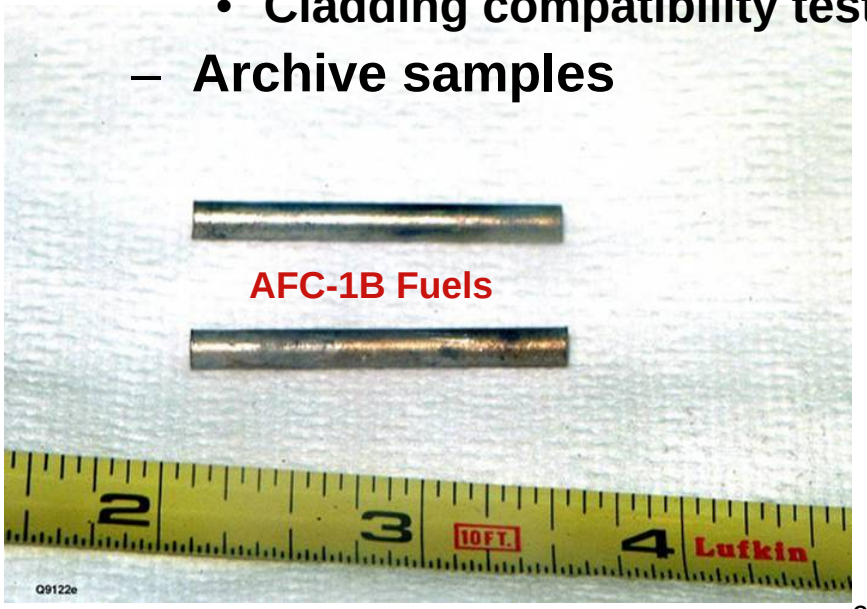


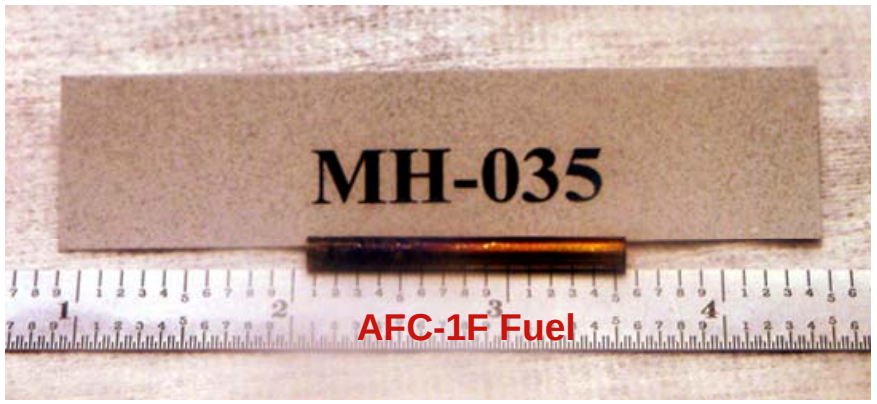
Metallic Fuel Fabrication



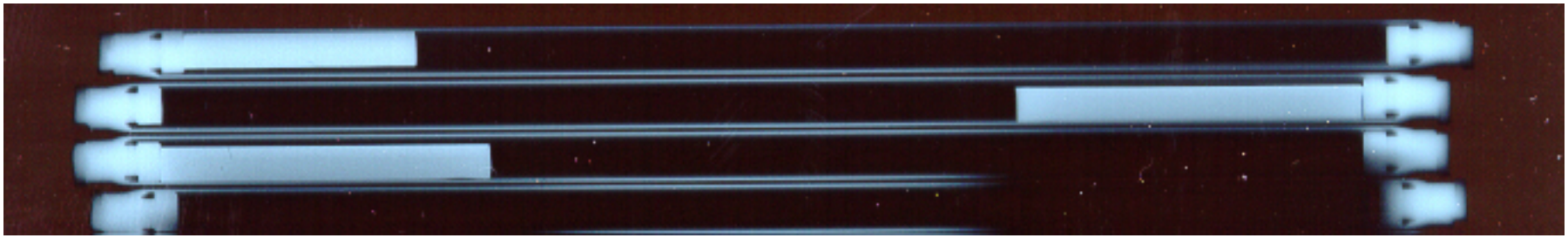
Metallic Fuels for AFC-1 Tests

- **Arc-Cast Pins Sectioned to Provide**
  - **Fuel specimens for irradiation tests**
  - **Samples for chemical and isotopic analysis**
  - **Samples for characterization**
    - **Microstructural analysis (XRD/SEM)**
    - **Thermal Analysis (DSC/DTA/TGA)**
    - **Cladding compatibility testing (diffusion couples)**
  - **Archive samples**





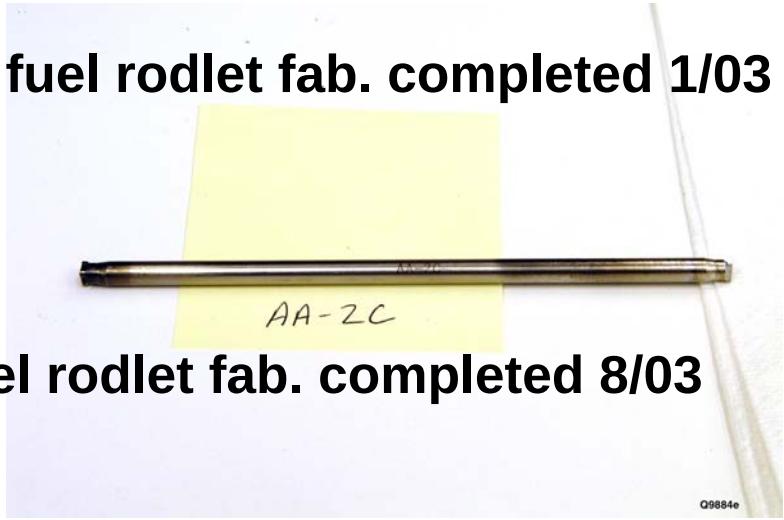
Metallic Fuel Rodlet Fabrication



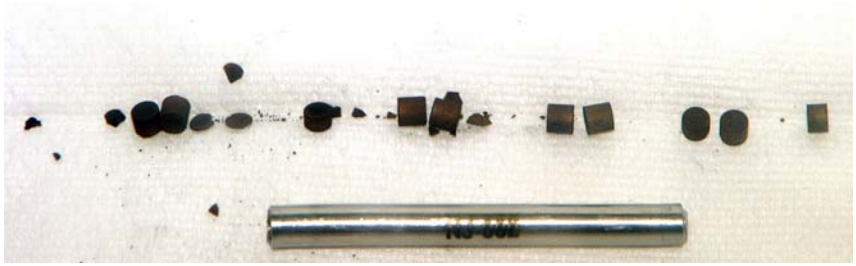
1. Fabricate jackets; load and settle sodium.
2. Load fuel on top of solid sodium; weld top end plug.
3. Weld inspection: visual exam, He leak testing, radiography.
4. Sodium heated above melting temperature; fuel column settled to bottom end plug.
5. Radiographic inspection of sodium level and slug position.
6. Fuel rodlet heated to ~500°C; sodium wets fuel and cladding.
7. Radiographic inspection of final slug position and sodium height.

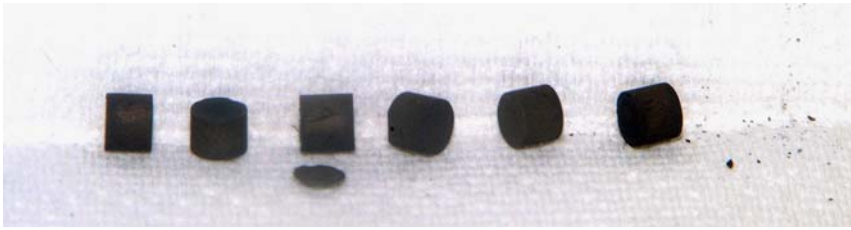
Fuel Rodlet Fabrication Status

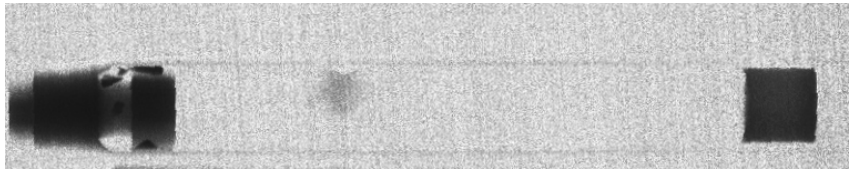
- AFC-1B,D non-fertile metallic fuel rodlet fab. completed 1/03
  - Pu-12Am-40Zr (2)
  - Pu-10Am-10Np-40Zr
  - Pu-40Zr
  - Pu-60Zr
- AFC-1F low-fertile metallic fuel rodlet fab. completed 8/03
  - U-29Pu-4Am-2Np-30Zr (2)
  - U-25Pu-3Am-2Np-40Zr (2)
  - U-34Pu-4Am-2Np-20Zr
  - U-28Pu-7Am-30Zr
- AFC-1A,C non-fertile nitride fuel rodlets fabricated 4/03
  - Rodlets not usable due to pellet fragmentation
  - AFC-1C (high BU) eliminated
  - AFC-1A consolidated with AFC-1E to AFC-1Æ
- AFC-1Æ non/low-fertile nitride fuel rodlet fabrication in progress but will likely not meet 09/03 milestone

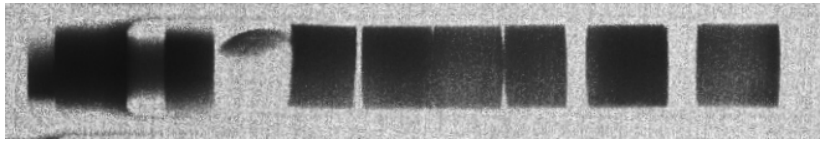


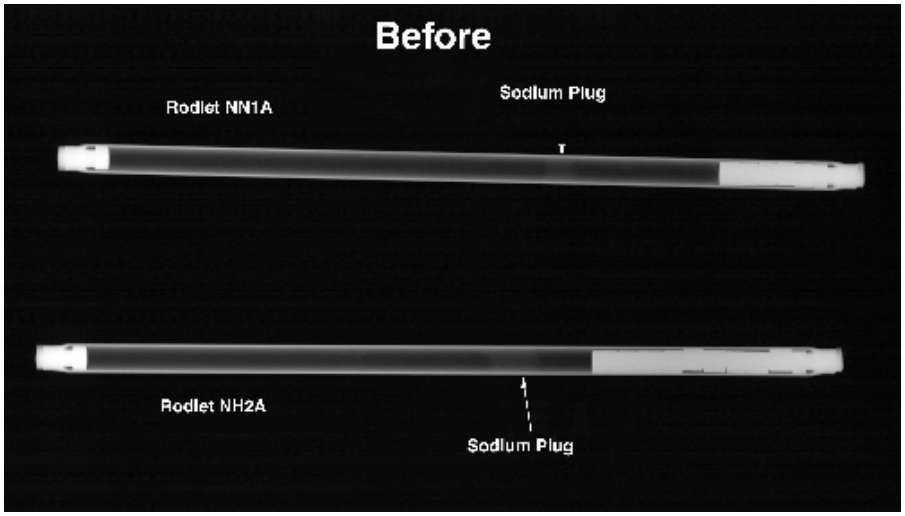
Nitride Rodlet Fabrication Demonstrated

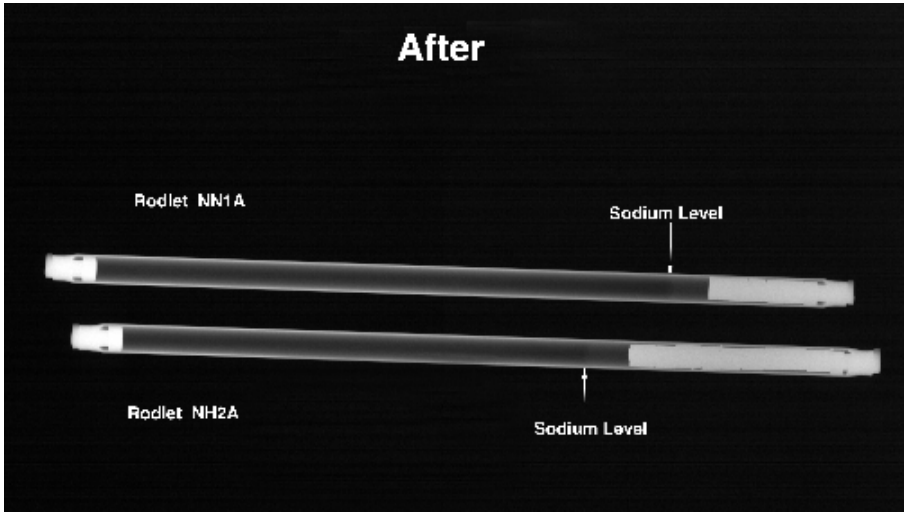








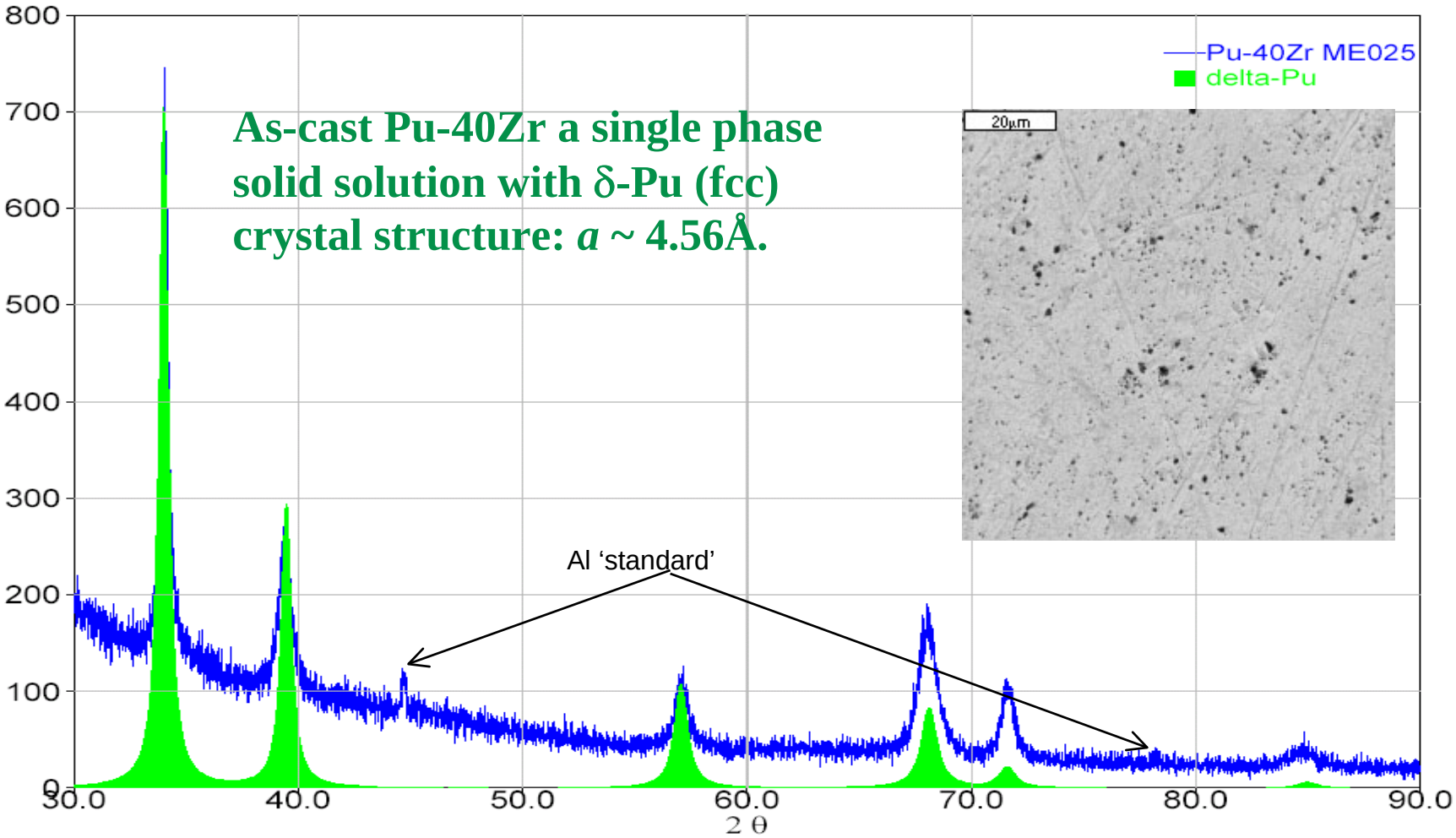




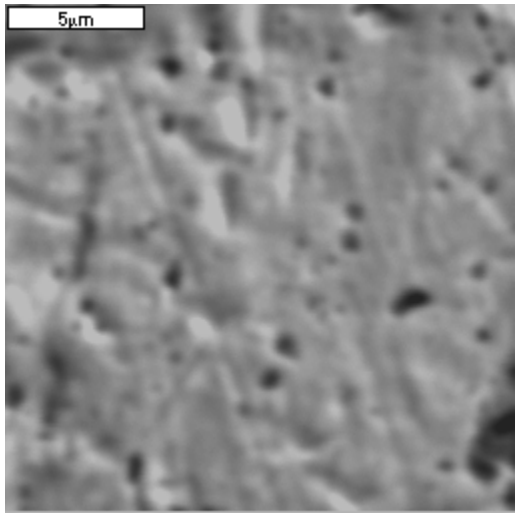
Metallic Fuel Characterization

- **Non-Fertile Metallic Alloys (FY03 complete)**
  - **Pu-12Am-40Zr**
  - **Pu-10Np-40Zr**
  - **Pu-10Am-10Np-40Zr**
  - **Pu-40Zr**
  - **Pu-60Zr**
- **Low-Fertile Metallic Alloys (in progress)**
  - **U-29Pu-4Am-2Np-30Zr**
  - **U-25Pu-3Am-2Np-40Zr**
  - **U-34Pu-4Am-2Np-20Zr**
  - **U-28Pu-7Am-30Zr**

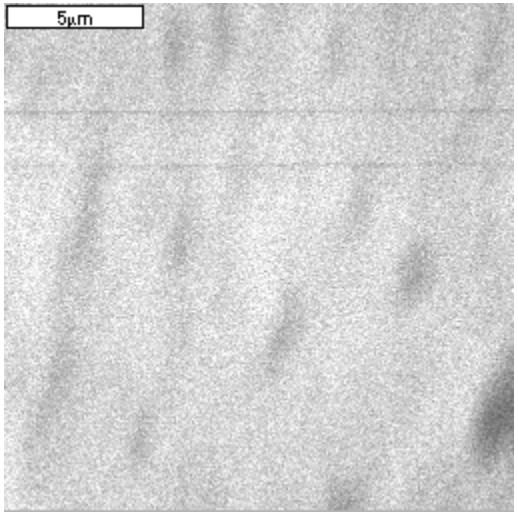
Microstructural Analysis of Pu-40Zr



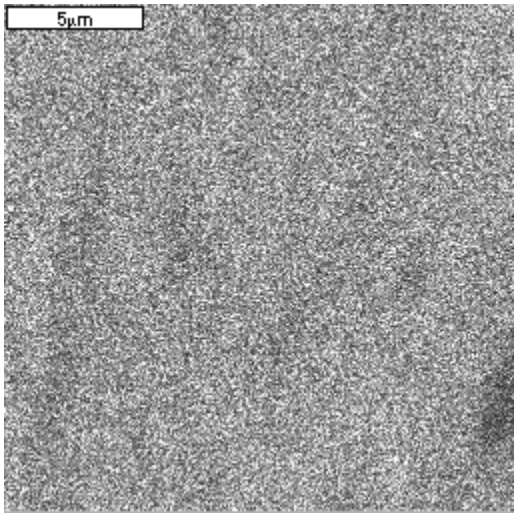
X-Ray Maps of Pu-40Zr



BSE Image



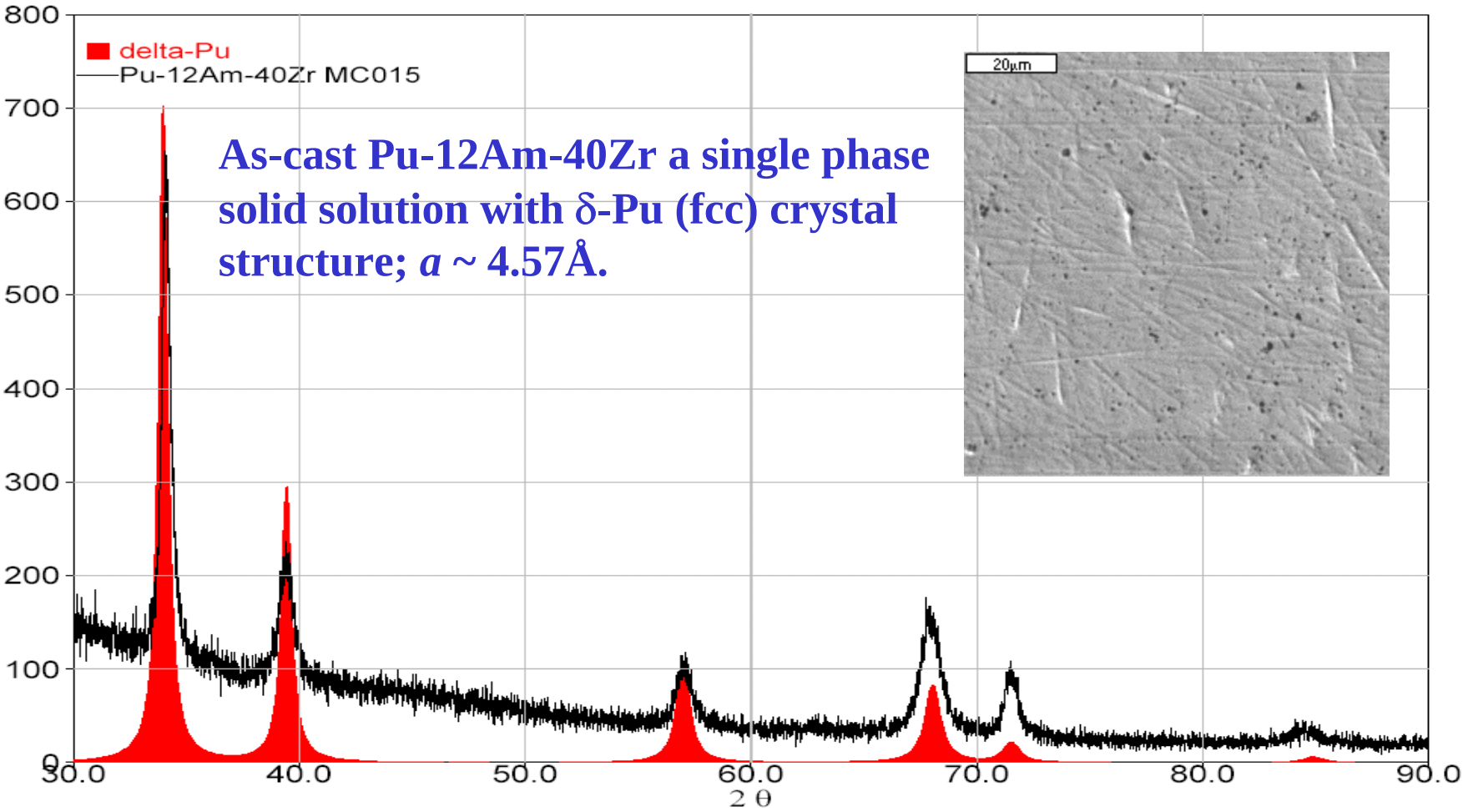
Pu



Zr

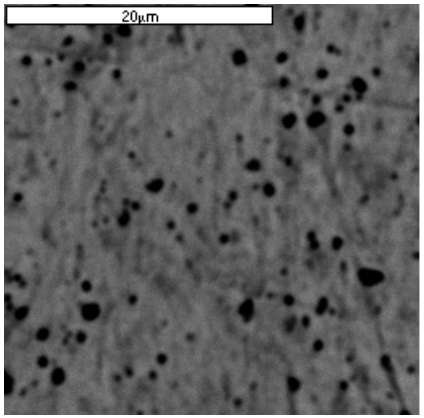
- **Alloy is single-phase**
- **Even distribution of Pu and Zr**
- **Agrees with published Pu-Zr phase diagram**

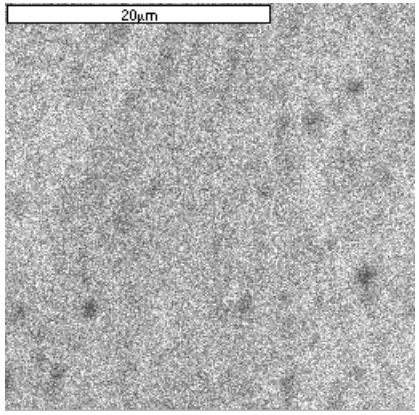
Microstructural Analysis of Pu-12Am-40Zr

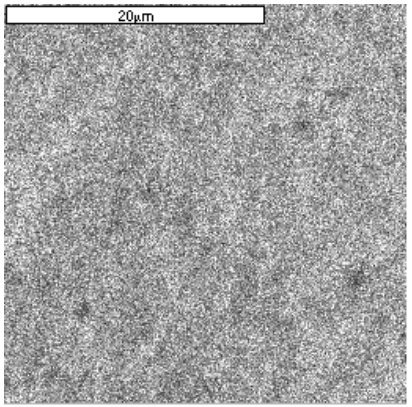


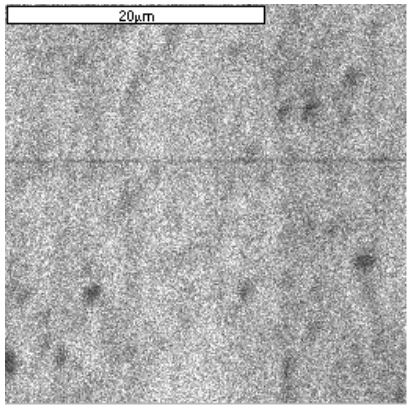
As-cast Pu-12Am-40Zr a single phase solid solution with δ-Pu (fcc) crystal structure; *a* ~ 4.57Å.

X-Ray Maps of Pu-12Am-40Zr



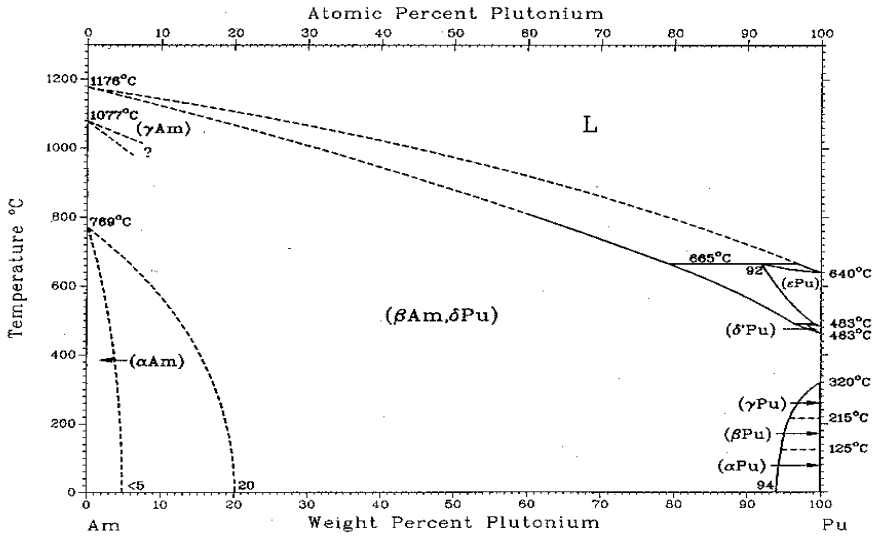




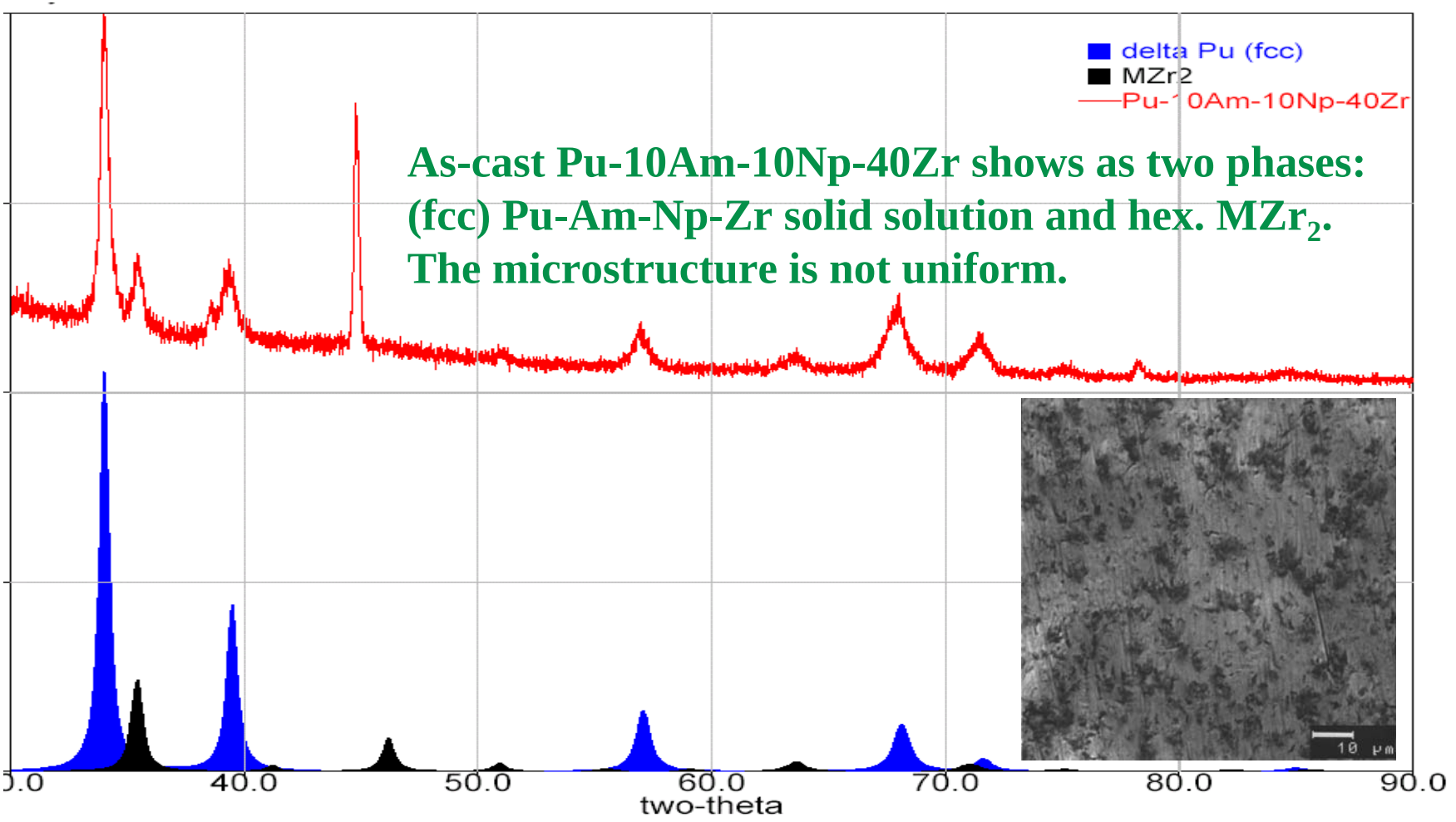


BSE Image Pu

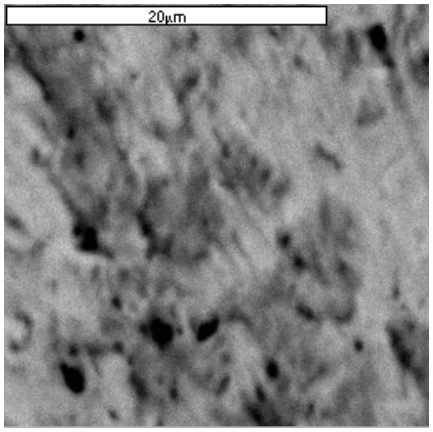
- **Alloy is single-phase**
- **Even distribution of Pu, Am, and Zr**
- **Am stabilizes δ-Pu**



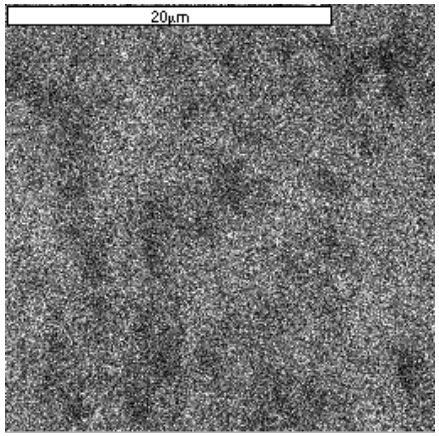
Microstructural Analysis of Pu-10Am-10Np-40Zr



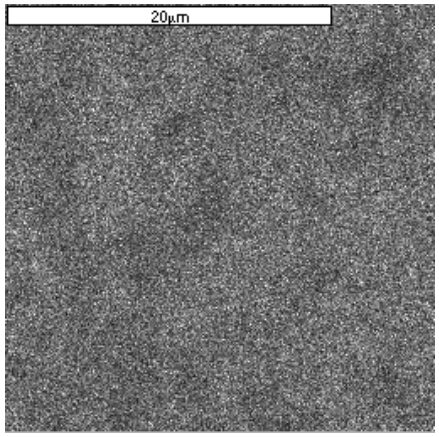
X-Ray Maps of Pu-10Am-10Np-40Zr



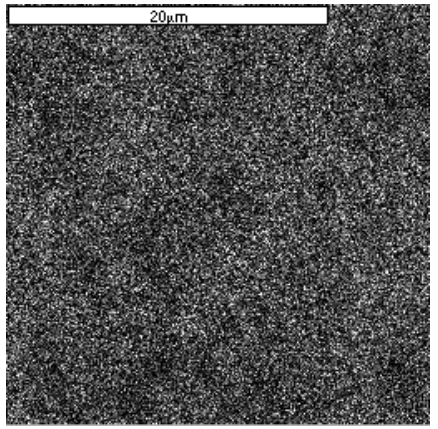
BSE Image



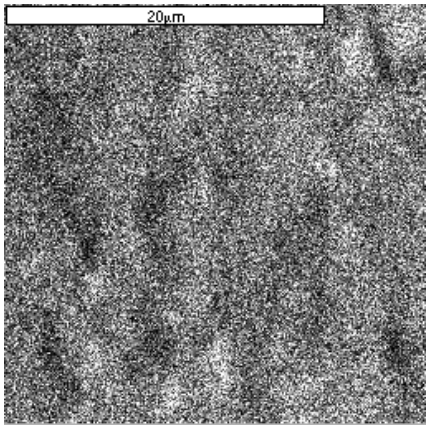
Pu



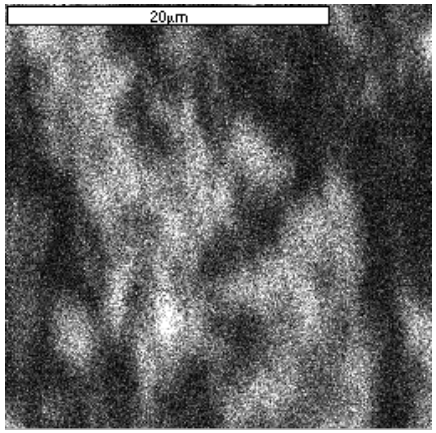
Np



Am



Zr



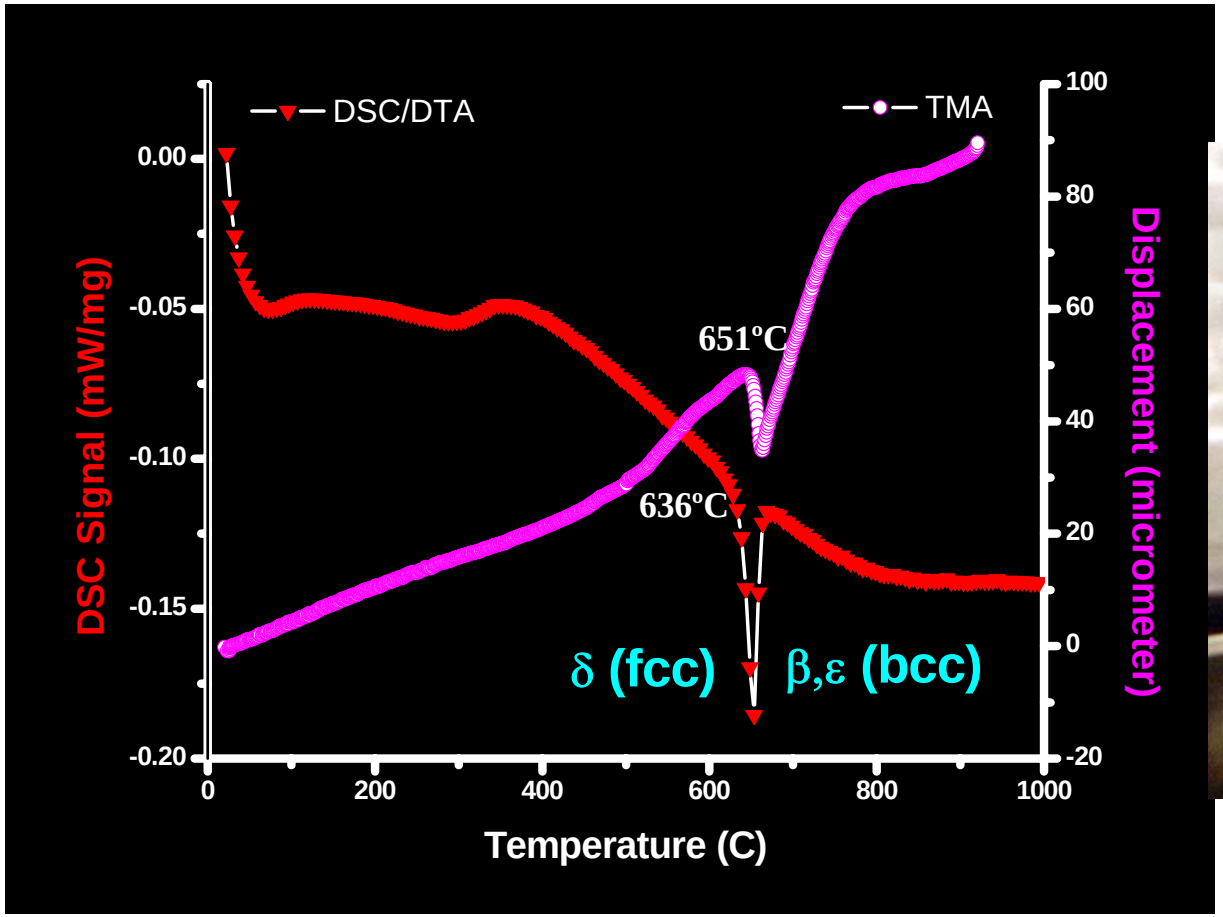
O

- **Pu, Np, and Am found in same areas of microstructure.**
- **Zr depleted in areas enriched in actinides.**
- **Globular phases enriched in oxygen, may be stabilizing the MZr_2 phase.**

Thermal Analysis of Non-fertile Alloys

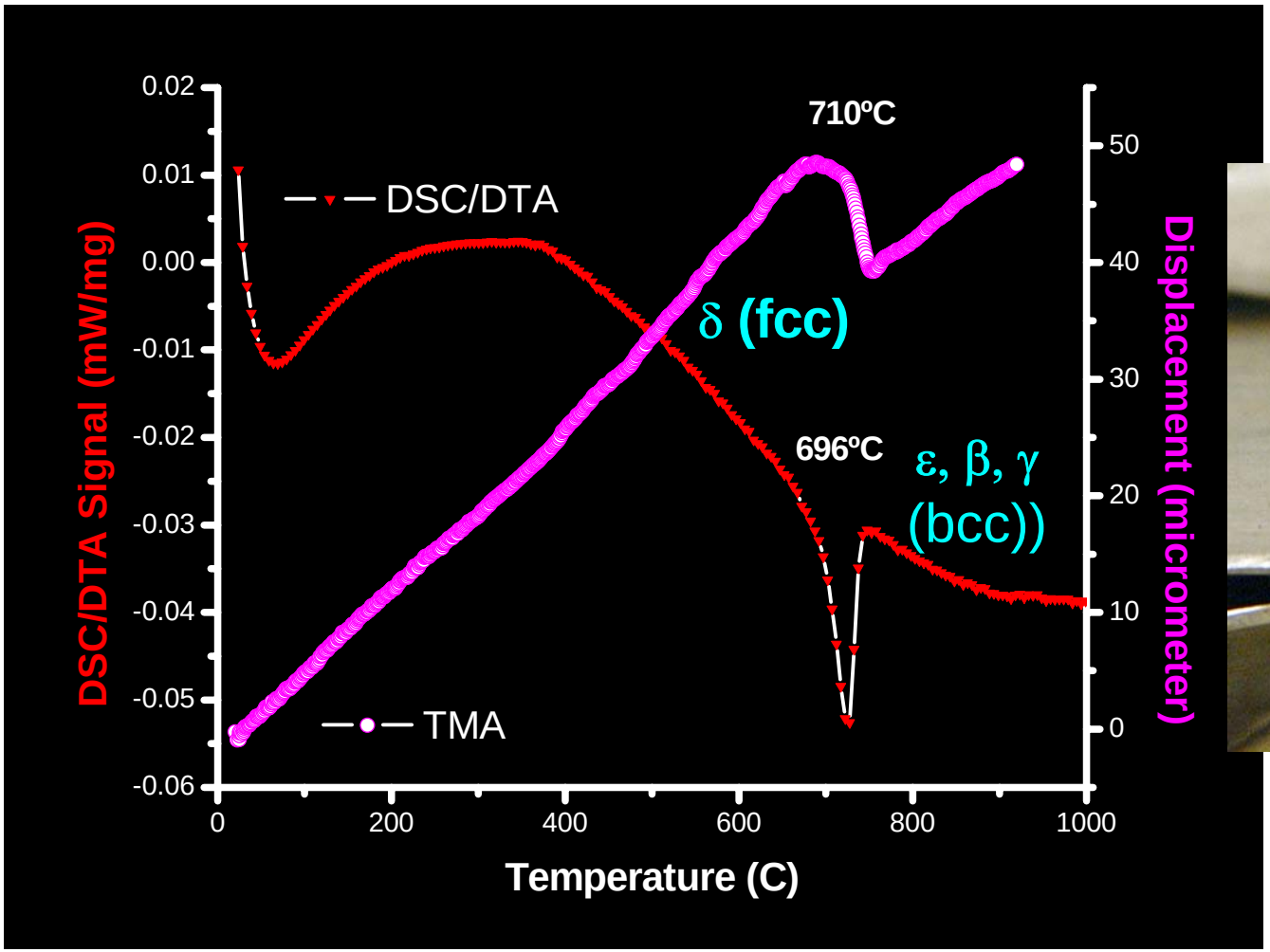
- **Identification of Phase Transitions up to 1000°C**
  - **Pu-12Am-40Zr**
  - **Pu-10Np-40Zr**
  - **Pu-10Am-10Np-40Zr**
  - **Pu-40Zr**
  - **Pu-60Zr**
  - **No melting observed in these alloys to 1000°C**
- **Analysis Techniques**
  - **Differential Scanning Calorimetry (DSC)**
  - **Differential Thermal Analysis (DTA)**
  - **Thermo-Mechanical Analyzer (TMA)**

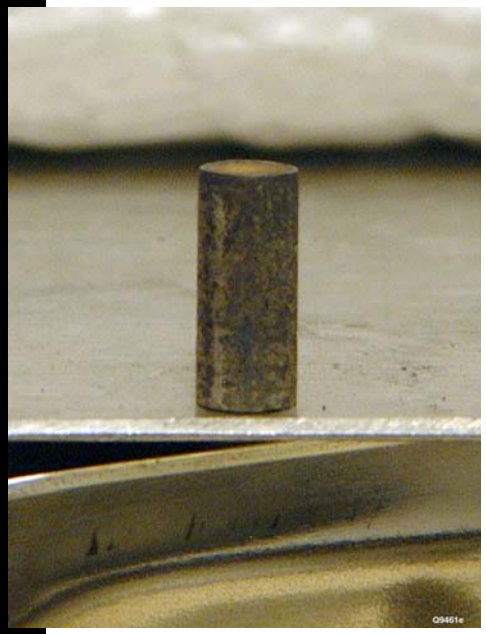
DSC/DTA/TMA Heating Curves
Pu-40Zr



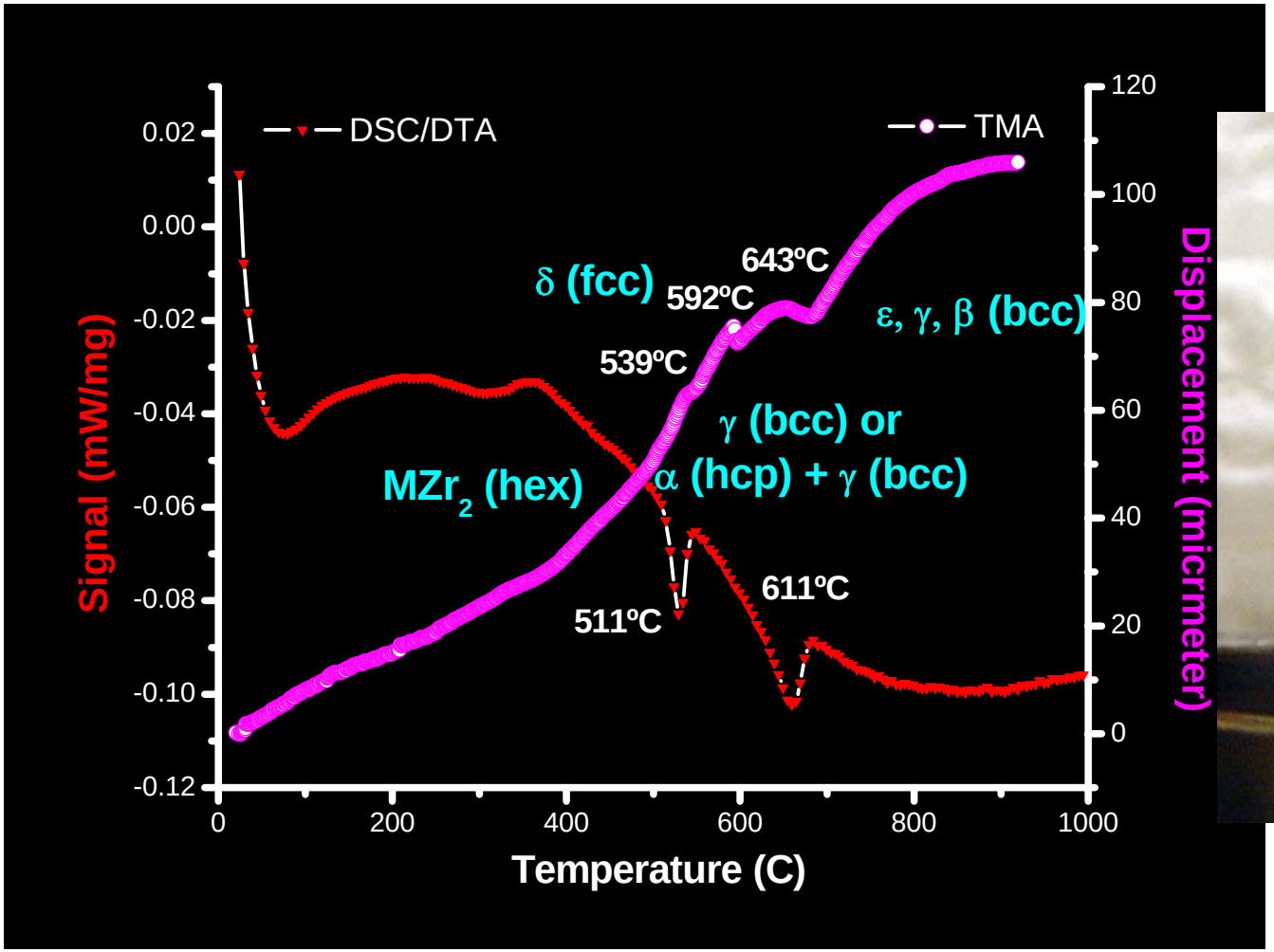
fcc to bcc transition from published phase diagram: 640°C

DSC/DTA/TMA Heating Curves
Pu-12Am-40Zr

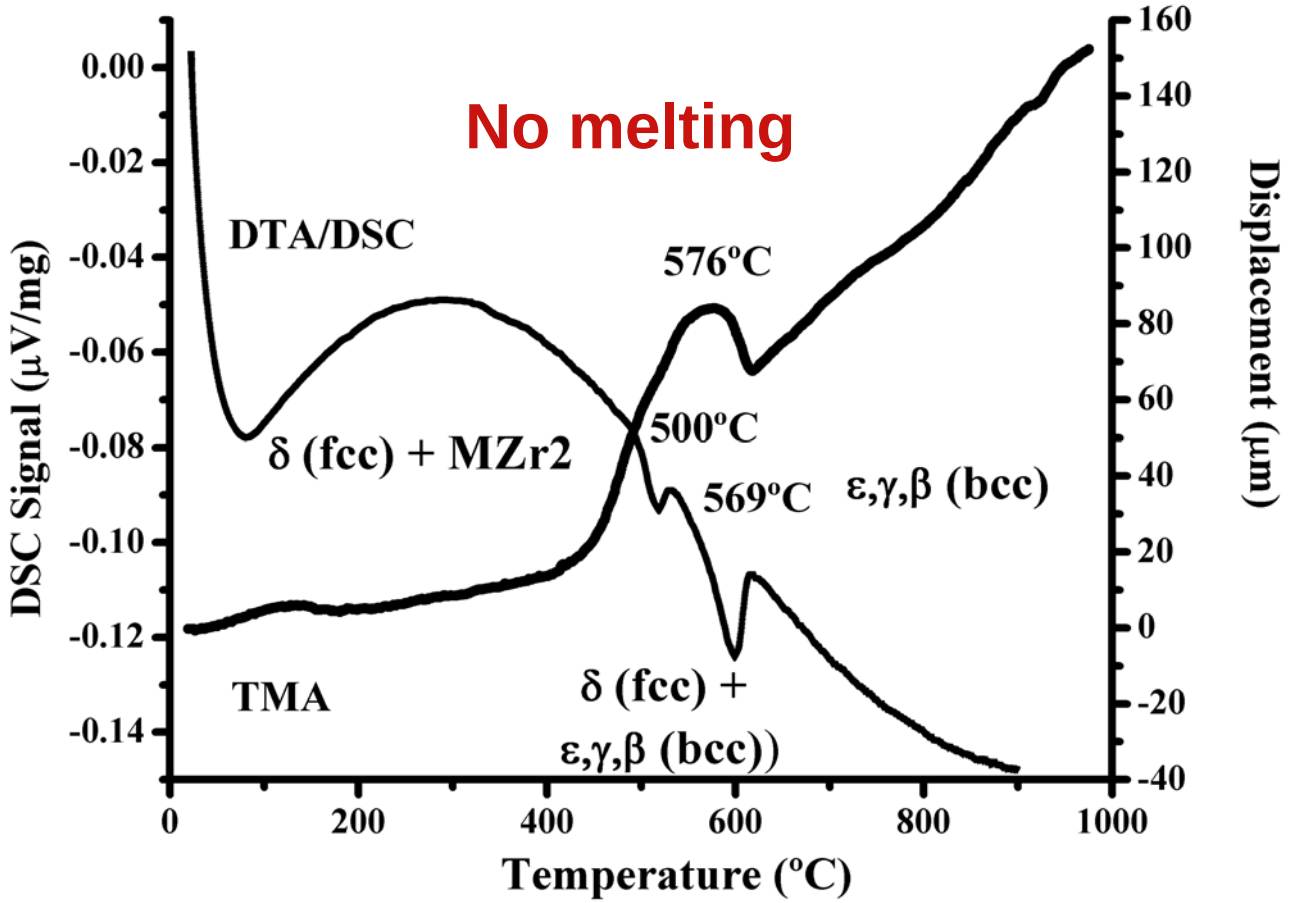




DSC/DTA/TMA Heating Curves
Pu-10Am-10Np-40Zr

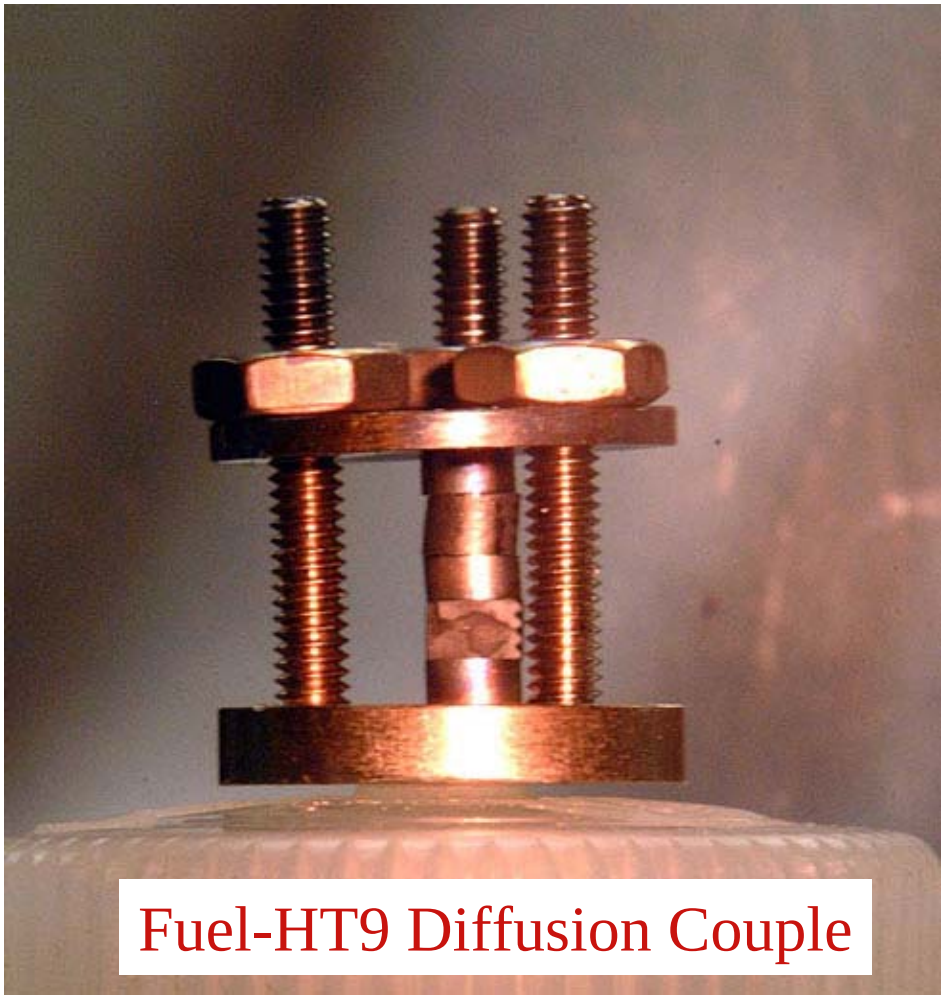


DSC/DTA/TMA Heating Curves
Pu-10Np-40Zr



Fuel-Cladding Chemical Interaction

- **Diffusion Couples**
  - **HT-9 (Type 422 SS) vs.**
    - **Pu-12Am-40Zr**
    - **Pu-10Np-40Zr**
    - **Pu-10Am-10Np-40Zr**
    - **Pu-40Zr**
    - **Pu-60Zr**
  - **Furnace anneals**
    - **50 to 200 hours**
    - **650°C**
    - **850°C**
  - **Analysis**
    - **SEM/EDS/WDS**

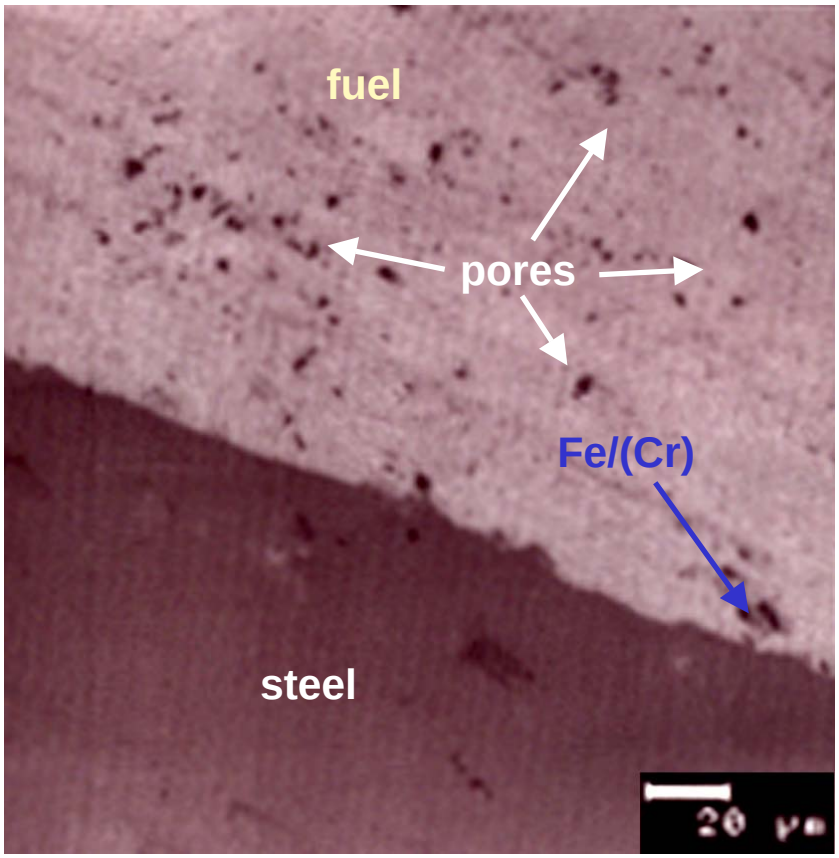


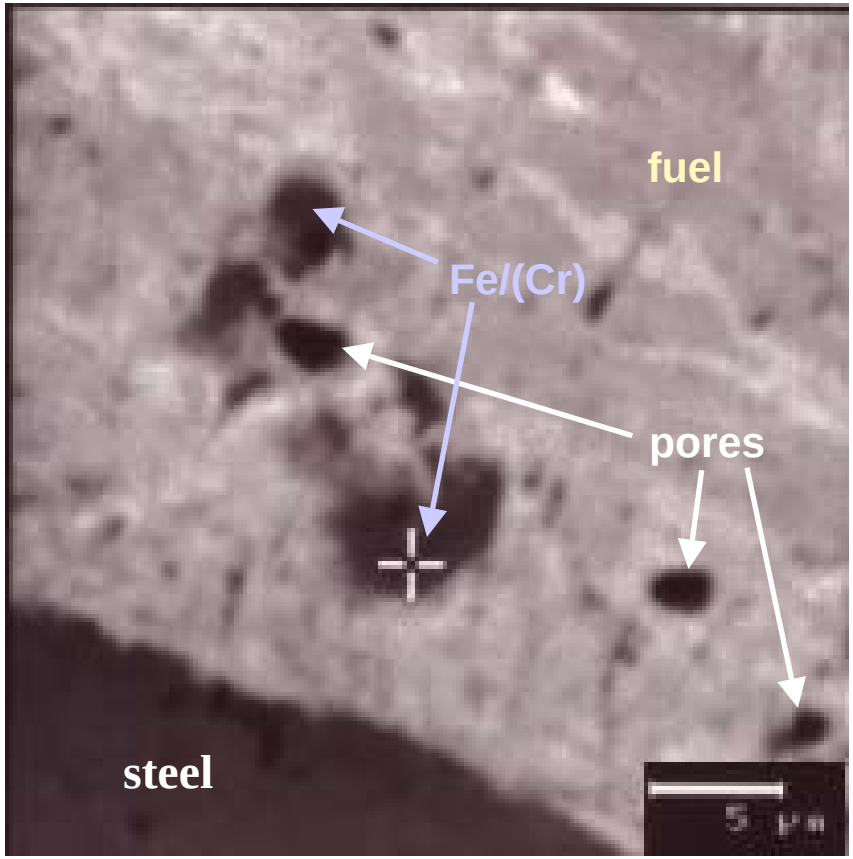
Fuel-HT9 Diffusion Couple

FCCI Results

- At 650°C
  - No uniform diffusion layers observed
  - Discrete Fe-rich globular precipitates observed penetrating into fuel alloy
- At 850°C
  - Complete interdiffusion of fuel alloy and cladding
  - Same discrete Fe-rich precipitates throughout fuel
  - Also discrete Zr-rich precipitates throughout fuel
  - No melting
- Conclusions
  - Fe-rich and Zr-rich phases have high melting points
  - No actinide-rich, low-melting phases observed
  - With no diffusion layers formed at fuel-clad interface, cladding should retain nominal mechanical properties

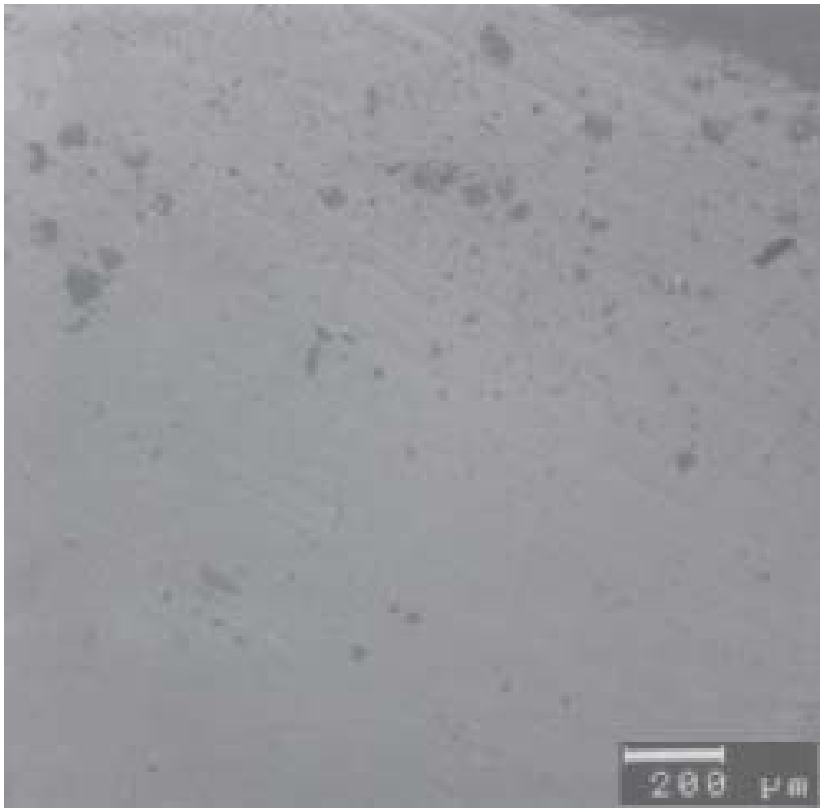
BSE Micrographs of Diffusion Couples (650ºC for 50 hours)



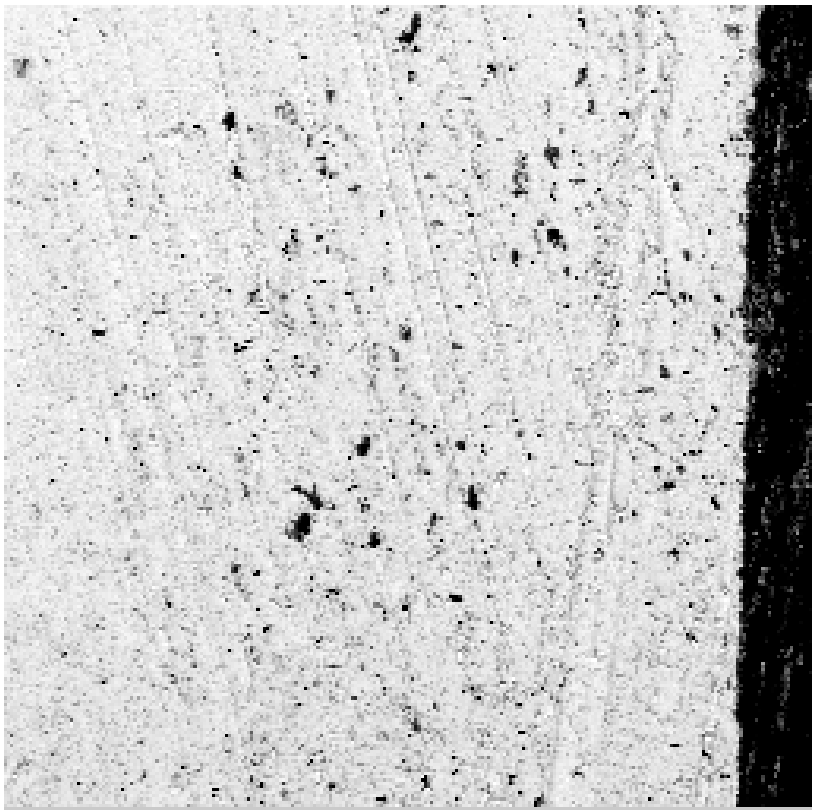


Pu-60Zr/422

BSE Micrographs of Diffusion Couples (650°C for 200 hours)



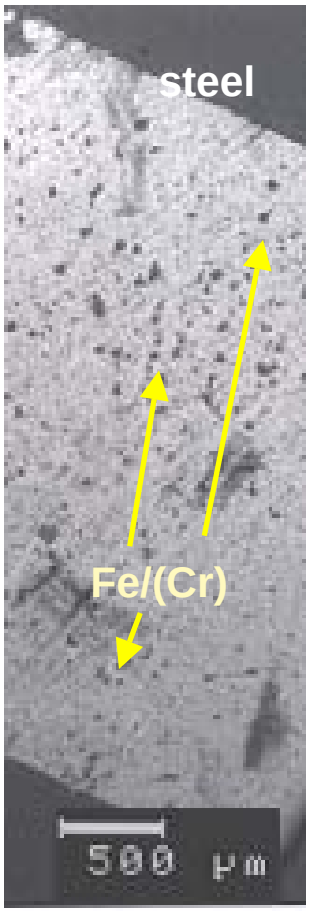
Pu-40Zr/422



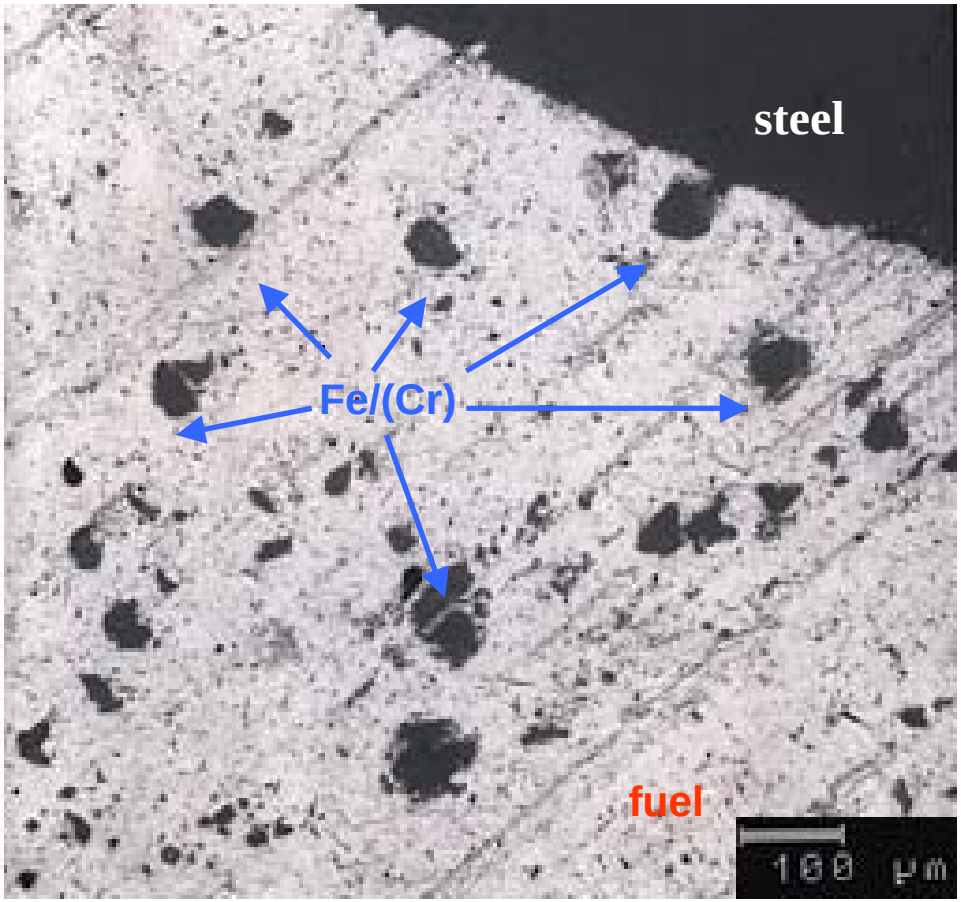
Pu-10Am-10Np-40Zr/422

- Fe/(Cr) deposits observed out to 1000 microns of interface
- Other dark features throughout fuel are pores

BSE Micrographs of Diffusion Couples (860°C for 50 hours)



steel



Pu-40Zr/422

Complete interdiffusion in couples with Pu-10Np-40Zr, Pu-12Am-40Zr and Pu-10Am-10Np-40Zr with similar structures

Irradiation Test Fabrication/Assembly

- **AFC-1B, -1D Test Capsules**
  - **Fabricated and assembled 5/03**
  - **Delivered to ATR on June 3, 2003**
  - **Irradiation in progress**
- **AFC-1Æ, -1F Test Capsules**
  - **Hardware fabrication complete**
  - **Assembly scheduled for 9/03**
  - **Irradiation to begin in 11/03**

Postirradiation Examination

- **Plans for Postirradiation Examination**
  - **AFC-1A,B,C,D PIE Plan issued in January 2003**
  - **AFC-1Æ,F PIE Plan issued in May 2003**
- **Preparations Initiated to Receive GE-2000 Cask at the Hot Fuel Examination Facility (June 2004)**